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SUBMERGED FLOW IN PARSHALL FLUMES

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ABSTRACT

Recent data collected in a 1-foot Parshall flume located in the Bureau of Reclamation's hydraulic laboratory indicate a significant discontinuity in the discharge/submergence relationship. There is a range of submergence over which two values of discharge can occur for the same submergence and upstream head. The data indicate errors as large as 12 percent can occur between the actual discharge and the discharge calculated by Parshall's method. A free flow equation and two equations that correct for submergence effects were developed. An equation was developed for each side of the discontinuity in the submerged zone. Further data collection and analysis are planned. Until this work is completed, it is recommended that 1-foot Parshall flumes be operated below 86 percent submergence and that the equation developed in this study be used to correct for submergence effects.

INTRODUCTION

Under submerged flow conditions discharge varies with upstream head (H_a) and submergence where submergence is the downstream head (H_b) divided by H_a. As an aid to the analysis of the functional relationship between these three variables, one variable should be held constant while the other two are varied. Previous studies of submerged flow in Parshall flumes [Parshall, 1928 and Skogerboe, et al., 1967] did not collect data at constant discharges, upstream heads, or submergence. As a result their data are widely scattered when plotted and visual analysis requires a significant amount of interpolation through the data. Data for this study were collected and analyzed at constant upstream heads; therefore, changes in flow regimes were more easily recognized.

This study was initiated to determine the best method to predict discharge in the submerged flow region. Parshall's equation and an equation recommended in a publication by Utah State University's College of Engineering Water Research Laboratory [Skogerboe, et al., 1967] were considered. Data collected at an H_a of 1.0 feet indicated a significant discontinuity in the discharge/submergence relationship not identified by previous researchers. Equations that more accurately predict discharge in the submerged flow region were then developed.

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STUDY METHODOLOGY

Piezometer taps (5/16-inch-diameter) were installed at the standard locations for H_a and H_b as recommended in the Bureau of Reclamation's Water Measurement Manual [USBR, 1984]. Stilling wells with hook gauges were used to measure H_a and H_b. H_a was also measured with a pressure transducer. A computerized PID (proportional integral derivative) control system was used to maintain a constant value of H_a. The controller adjusted discharge by regulating a gate valve to maintain the target value of H_a. The degree of submergence was controlled by adding or removing tailboards at a canal section 16 feet downstream of the flume. Adding and removing tailboards have the effect of increasing and decreasing downstream resistance. The controller would automatically adjust the discharge to maintain H_a. At some data points, a constant value of H_a was maintained by manually controlling the gate valve. These data points matched well with the data points obtained with the use of the controller.

Data were collected at upstream heads of 0.6, 1.0, 1.5, and 2.0 feet. All H_a and H_b data values are the average of six readings obtained with the hook gauge. If the average H_a reading differed more than 0.3 percent from the target value of H_a the data point was discarded.

RESULTS

The data at upstream heads of 0.6, 1.0, and 1.5 feet indicate a discontinuity in the submergence/discharge relationship. A clear difference in the appearance of the flow between data that plots to the right of the discontinuity and data that plots to the left of the discontinuity (fig. 1) was noted at each of these upstream heads. Figure 1 shows the data at upstream heads of 1.0 and 1.5 feet. Flow at all data points that plot to the right of the discontinuity are characterized by a "V" shaped surface disturbance in the flume throat. Flow at all data points that plot to the left of the discontinuity are characterized by a "U" shaped surface disturbance in the flume throat. At upstream heads of 0.6 and 1.0 foot the transition zone between flow with a "V" shaped surface disturbance and flow with a "U" shaped surface disturbance is sharp and occurs over a very small range of discharge. A wider transition zone between the two types of surface disturbance occurs at an H_a of 1.5 feet; between 5.2 ft^3/s and 5.8 ft^3/s the flow oscillates between a "V" shaped and a "U" shaped disturbance.

The data at an H_a of 2.0 feet do not indicate a clear discontinuity when plotted. However, flow above 94 percent submergence is characterized by a "U" shaped surface disturbance and flow below 90 percent submergence is characterized by a "V" shaped surface disturbance. Between 90 and 94 percent submergence the discharge varies from 8 ft^3/s to 9 ft^3/s. In this discharge range the flow oscillates between a "U" shaped and a"V" shaped surface disturbance.

Data at submergence of 60 percent or less were used to develop a free flow equation. A linear regression analysis resulted in the equation:

$$Q = 3.95\ H_a^{1.55} \qquad (1)$$

where Q is discharge in ft^3/s and H_a is upstream head in feet.

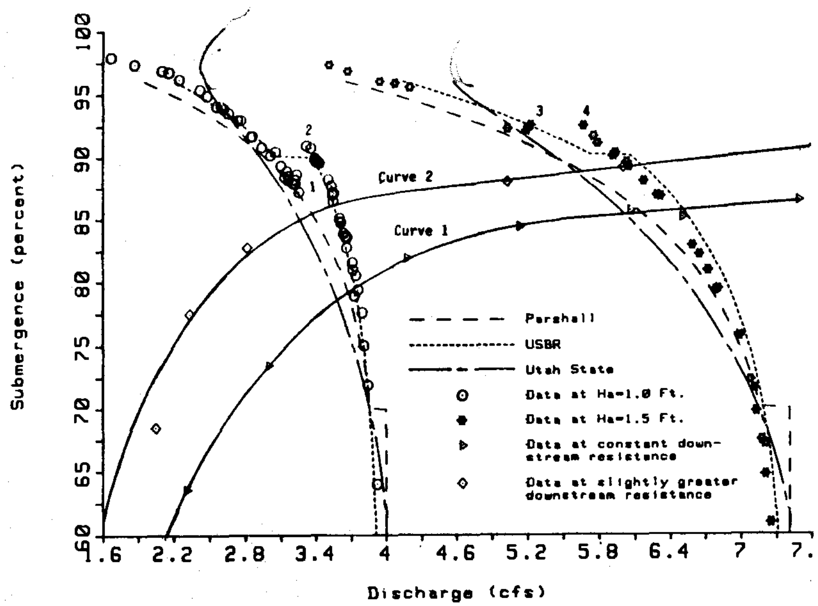

Figure 1. - Plot of discharge versus submergence.

Discharge at data points with submergence above 60 percent were subtracted from the discharge calculated with equation 1 to obtain the reduction in discharge due to submergence. Multiple regression analysis of data to the right of the discontinuity at all values of H_a resulted in the equation:

$$DQ = 0.000132\ H_a^{2.123}\ e^{9.284\ S} \qquad (2)$$

in which DQ is the reduction in discharge due to submergence effects in ft^3/s, S is the percent submergence divided by 100, and e is equal to 2.7183.

Multiple regression analysis of data to the left of the discontinuity resulted in the equation:

$$DQ = .0000324\ e^{11.333\ S}\ e^{1.567\ S\ \log(H_a)} \qquad (3)$$

The total discharge at submergence of 60 percent or greater is determined by subtracting either equation 2 or 3 from equation 1. The curves on figure 1 labeled "USBR" were computed with equations 1, 2, and 3. These equations also fit the data at upstream heads of 0.6 and 2.0 feet much better than either Parshall's or Utah State's equation. More data and analysis are required before the location of the discontinuity as a function of H_a can be clearly defined. Until then it is recommended that 1-foot Parshall flumes be operated below 86 percent submergence, therefore, only equation 2 should be used to correct for submergence effects.

ANALYSIS

It is generally believed that only H_a is needed to determine discharge through Parshall flumes when supercritical flow occurs in the flume throat. However, this is true only if the flow always passes through critical depth at the same location. If the location of critical depth changes, the distance between critical depth and the measuring point for H_a will also change. Thus, the length available for development of the flow profile will change. It is believed the curvature of the data to the right of the discontinuity is due to the critical depth location shifting downstream as the submergence is increased. At low submergence the flow passes through critical depth on the horizontal section upstream of the throat. As resistance to flow is increased the flow requires a greater distance to reach critical depth. Thus the location where critical depth occurs moves downstream along the horizontal section. The result is a longer H2 flow profile between the critical depth location and the measuring point for H_a. The depth at H_a will now be greater for the same discharge due to the longer H2 flow profile. To maintain the same depth at H_a the discharge must be lowered. Froude numbers obtained at the downstream end of the crest at an H_a of 1.5 feet verify that flow is passing through critical depth at much higher submergence than previously thought. The Froude number of the flow at point 4 (fig. 1) is 1.1, indicating supercritical flow on the end of the flume crest. The Froude number of the flow at data points to the right of the discontinuity steadily increases as the submergence decreases. The "V" shaped surface disturbance at data points to the right of the discontinuity is therefore a hydraulic jump. For discussion of flow profiles refer to pages 222-237 in "Open Channel Hydraulics" [Chow, 1959].

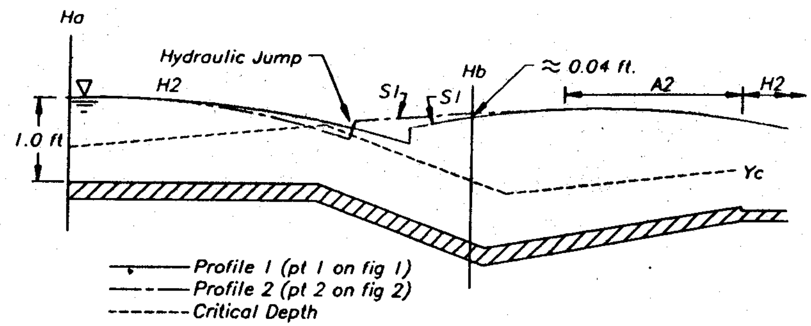

Figure 2. - Flow profiles in test flume (1-ft throat width).

The Froude number of the flow at point 3 (fig. 1) is 0.9 on the end of the flume crest, indicating subcritical flow. Since flow at H_a is subcritical, the only possible flow profile along the horizontal section is an H2 profile. The only profile possible on the steep section is an S1 profile since the flow does not pass through critical depth while on the horizontal section. An H2 profile cannot make a smooth transition into an S1 profile. It is believed the "U" shaped surface disturbance is the result of an H2 profile intersecting an S1 profile. The Froude number of the flow at data points to the left of the discontinuity continues to decrease as the submergence is increased.

Flow profile 1 on figure 2 corresponds to point 1 on figure 1. Flow profile 2 corresponds to point 2. A very slight change in downstream resistance to flow results in the plot of the data changing from point 1 to point 2 or vice versa. The change in discharge between point 1 and 2 is less than 2 percent; therefore, critical depth of the flow is virtually the same at both data points. A hydraulic jump occurs in the flow of point 2 at approximately the location shown in figure 2. The sequent depth of the hydraulic jump is approximately the water elevation in the adversely sloped section. There is little change in water elevation between a section immediately after the hydraulic jump and the measuring point for H_b. It was noted that at point 1 the surface disturbance had moved approximately 1 foot downstream of the hydraulic jump location for flow profile 2. The flow disturbance of profile 1 is due to the intersection of an H2 profile with an S1 profile. The H2 profile must extend into the steep section since the flow disturbance occurs on the steep section. It is believed the S1 profile also extends beyond the steep section onto the adverse section as shown. Since the flow at point 1 does not go through a hydraulic jump, the flow must follow an S1 profile up to the A2 profile. The difference in H_b between point 1 and 2 for virtually the same discharge is due to the S1 profile of the flow at point 1 beginning at a lower water elevation than the S1 flow profile of point 2 and to the H2 and S1 profiles extending beyond the horizontal and steep sections respectively. In the transition zone at upstream heads of 1.5 and 2.0 feet it was noted that, at a constant discharge, the flow profile oscillated between the two types shown in figure 2.

Two discharge curves are shown on figure 1 for the 1-foot test flume in the hydraulic laboratory. Each curve represents the discharge/submergence relationship for a constant tailboard configuration and therefore a constant downstream resistance. A slight increase in downstream resistance caused the discharge/submergence relationship to shift from curve 1 to curve 2 (fig. 1). In a field situation a change in downstream resistance can be caused by construction of a new check gate structure, a change in check gate position, or vegetation growth. These changes will probably shift the discharge curve more than shown on figure 1.

CONCLUSIONS

A significant discontinuity was found to occur in the submergence/discharge relationship of 1-foot Parshall flumes. The discontinuity is believed to be due to the flow regime changing from a state in which critical depth occurs on the horizontal section to a state in which the flow is subcritical throughout the flume. The data indicate that supercritical flow occurs on the crest at much higher submergence than previously thought. A free flow equation was developed from data at 60 percent submergence or less. Two equations that correct for reduction in discharge due to submergence effects, one for each side of the dicontinuity, were developed from data at submergence greater than 60 percent.

Until further data collection and analysis are performed it is recommended that 1-foot Parshall flumes be operated below 86 percent submergence. For submergence less than 60 percent equation 1 can be used alone. For submergence between 60 and 86 percent equation 2 should be subtracted from equation 1.

APPENDIX 1 - REFERENCES

1. Parshall, R. L., "The Improved Venturi Flume," Bulletin 336, Colorado Agricultural College, Colorado State University, 1928.

2. Skogerboe, G. V., Hyatt, M. L., England, J. D., Johnson, R. J., "Design and Calibration of Submerged Open Channel Flow Measurement Structures, Part 2 - Parshall Flumes," Report WG31-3, College of Engineering, Utah State University, 1967.

3. United States Bureau of Reclamation, "Water Measurement Manual," 1984.

4. Chow, V. T., "Open Channel Hydraulics," McGraw-Hill, 1959.

APPENDIX 2 - U. S. Customary - SI Conversion Factors

1 inch = 25.4 millimeters
1 foot = 0.3048 meters
1 ft^3 = 0.0283 cubic meters